Developments at NIST on Traceability in Dimensional Measurements

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ABSTRACT

This paper reports to the international community on recent developments in technical policies, programs, and capabilities at the U.S. (United States) National Institute of Standards and Technology (NIST) related to traceability in dimensional measurements. These developments include: formal NIST policies on traceability and assuring quality in the results of the measurements it delivers to customers in calibration and measurement certificates, and a program to support the achievement of traceability to the SI (International System of Units) unit of length in dimensional measurements by manufacturers without direct recourse to a National Metrology Institute (NMI) for dimensional calibrations.

1. INTRODUCTION

Traceability in dimensional measurements, which historically has been a concern of calibration laboratories, is emerging as an issue to be addressed on the factory floor. At the heart of this issue are three major trends to which the U.S. (United States) National Institute of Standards and Technology (NIST) is responding in developing new technical policies, programs, and capabilities. The trends include:

- continuing tightening of manufacturing tolerances,
- a shift from national to international standards governing industrial metrology, and
- the rise of quality assurance and laboratory accreditation programs.

The continuing tightening of manufacturing tolerances, particularly in high-technology industries, now requires in some cases (e.g., fuel injectors) that dimensional measurements in the manufacturing facility be of the highest metrological quality attainable, that is, having uncertainty equal or smaller than that attained through recourse to an NMI (National Metrology Institute). The current trend from national to international documentary standards governing industrial metrology increasingly requires that domestic manufacturers be responsive to customer specifications based on international product standards. Among international documentary standards governing industrial metrology is an emerging suite of product standards with requirements that dimensional measurement made on manufactured workpieces conform to design specifications that explicitly address the issue of measurement uncertainty. Finally, the rise of accreditation programs based on standards such as ISO 9000 and ISO 17025 has greatly increased interest in traceability issues at the factory floor level. With the steadily increasing numbers of accredited laboratories, traceability issues and problems will become more prominent in the coming years.

This paper reports to the international community on recent developments in technical policies, programs, and capabilities at NIST related to traceability in dimensional measurements. Section II describes briefly the new NIST policy on traceability. Section III identifies some alternative paths of traceability from an NIST perspective. Section IV describes an NIST program to support the achievement by manufacturers of traceability in dimensional measurements to the SI unit of length without recourse to an NMI for dimensional calibrations. Finally, Section V identifies current questions on traceability in dimensional measurements for NIST that may also be issues for other National Measurement Institutes.

2. NIST POLICY ON TRACEABILITY

As the national metrology institute for the United States, NIST provides calibrations, standard reference materials, standard reference data, test methods, proficiency evaluation materials, measurement quality assurance programs, and laboratory accreditation services that assist a customer in establishing traceability of results of measurements or values of standards. To document its view of its role with respect to traceability, NIST has adopted a policy on traceability (http://www.nist.gov/traceability) which states that NIST:

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1. Adopts for its own use and recommends for use by others the definition of traceability provided in the most recent version of the *International Vocabulary of Basic and General Terms in Metrology* (VIM) [1]: "property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties." (ISO VIM, 2nd ed., 1993, definition 6.10)
2. Establishes traceability of the results of its own measurements and values of its own standards and of results and values provided to customers in NIST calibration and measurement certificates, operating in accordance with the *NIST System for Assuring Quality in the Results of Measurements Delivered to Customers in Calibration and Measurement Certificates*.
3. Asserts that providing support for a claim of traceability of the result of a measurement or value of a standard is the responsibility of the provider of that result or value, whether that provider is NIST or another organization; and that assessing the validity of such a claim is the responsibility of the user of that result or value.
4. Communicates, especially when claims expressing or implying the contrary are made, that NIST does not define, specify, assure, or certify traceability of the results of measurements or values of standards except those that NIST itself provides, either directly or through an official NIST program or collaboration.
5. Collaborates on development of standard definitions, interpretations, and recommended practices with organizations that have authority and responsibility for variously defining, specifying, assuring, or certifying traceability.
6. Develops and disseminates technical information on traceability and conducts coordinated outreach programs on issues of traceability and related requirements.

In addition to the statement of its organizational policy on traceability, NIST also developed a set of related supplementary materials available at its web site, including answers to questions frequently asked by customers of NIST measurement services. The policy and supplementary materials together are intended to serve as a resource for NIST customers. NIST welcomes your comments on these documents - what is useful, what could be improved, what could be added to make them more usable to its customers. The text may be viewed at www.nist.gov/traceability. Comments may be sent to traceability@nist.gov.

3. INDUSTRIAL MEASUREMENTS AND ALTERNATIVE PATHS OF TRACEABILITY

According to its VIM definition, which NIST as a matter of policy has adopted, traceability is the property of the result of a measurement by which it is related to a stated reference, usually a national or international standard. In the area of dimensional measurements, the international standard is the meter, one of the seven basis units of the International System of Units (the SI). The meter is defined in terms of the speed of light and the unit of time, the second.

3.1 Measurand specific traceability through an NMI

Historically, the classic traceability chain was characterized by a chain of physical comparisons to a dimensional calibration performed by a National Measurement Institute. Colloquially, this is referred to as "traceability to the SI through an NMI". Furthermore, it was typical for the same measurand to be propagated down the chain, for example, calibrated gauge blocks were used to calibrate other gauge blocks. While this measurand specific approach is ideal for the needs of calibration laboratories, it has limited applicability in the industrial measurement environment.

3.2 Non-measurand specific traceability through an NMI

The recent emphasis on the traceability of industrial measurements strains the traditional measurand specific approach since the number and variety of industrial measurements is enormous. NMI's have neither the calibration programs nor the capacity to calibrate a "master" artifact for every industrial component currently being inspected. Furthermore, such a program would be time consuming and prohibitively expensive both for the NMIs and industry. To address the diversity of industrial measurements, alternatives to the classic (measurand specific) path of traceability are desirable.

The intent of traceability is to provide a quality system for measurements. It ensures that all dimensional measurements have a common and consistent origin (the meter), and an uncertainty statement that describes the accuracy of measurement results as they propagate through the chain. One generalization of the classic traceability chain is to employ geometrically simple artifacts (e.g., gauge blocks) that have measurand specific traceability through an NMI and then subsequently use these artifacts as the connection to the SI unit in a calibration process that involves different measurands. For example, calibrated length standards traceable back to an NMI can be used to calibrate a coordinate measuring machine (CMM) for its ability to measure point-to-point length, and then the CMM can be used to measure different measurands, such as the concentricity of two bores. In this scenario connection to the SI unit is made with relative ease using simple length standards, while the uncertainty statement of a subsequent measurement of a different measurand is a complex calculation.[†] Nevertheless, the process can yield traceable measurement results. We point out that the "unbroken chain of comparisons" to the SI unit now involves different measurands and is best interpreted as an "unbroken chain of information" between the "input" (calibrated length standards) and the "output" (subsequent CMM measurements).

3.3 Traceability indirectly through an NMI

While the most common form of the traceability chain is directly through an NMI, that is, at the beginning of the traceability chain lies a calibration report issued from an NMI, it is not the only traceability path. Typically, these alternative routes involve some reproducible physical effect that has been well studied and assigned a numerical value. Although the particular instance of the physical effect used to provide traceability might not have been directly compared to another calibrated object, the physical effect has been studied using traceable measurements and this provides an "unbroken chain of information" back to the SI unit. In general, using a particular instance of a physical effect may have considerably more uncertainty associated with the assigned value than the case that has been directly compared to the reference standard, since the reproducibility of the effect must be taken into account. We now provide some examples of this path of traceability.

The first of these paths of traceability to the SI not directly through an NMI would entail someone other than an NMI employing local, practical realization of the meter using one of the recommended means, such as laser interferometry with the frequency/ vacuum wavelength of the laser referenced to the frequency/ vacuum wavelength of a recommended radiation, such as that of an iodine-stabilized HeNe laser. Both iodine-stabilized HeNe lasers and lasers with frequency/ vacuum wavelengths referenced to iodine-stabilized HeNe lasers are commercially available. Although the meter is defined in terms of time, NMIs have determined that a specific absorption line of an iodine cell (under specified conditions) can provide a reproducible link back to the unit of length. The iodine cell, when appropriately used to stabilize a HeNe laser, serves as a transfer standard of information leading back to the SI unit. Similar comments apply to other recommended radiation sources such as spectroscopic lamps, e.g., Krypton lamps, since they are very reproducible optical frequency standards even though a particular lamp has not been directly compared to the SI unit.

In some applications that are relatively low accuracy, other radiation sources (beyond those recommended in the *mise en pratique* [2]) can be used. For example, flatness measurements performed by interferometry can be conducted using any well known spectroscopic line, e.g., the Helium yellow line at 587.6 nm. Since deviations from flatness are small, the tabulated emission frequencies of spectroscopic sources (often published by NMIs as standard reference data) are sufficiently accurate for this application. In this case the unbroken chain of information flows through the published standard reference data involving the spectroscopic sources.

Another path of traceability to the SI not directly through an NMI would entail someone other than an NMI making a dimensional measurement based, for example, upon counted silicon (Si) lattice spacings. The lattice spacing of silicon has the status of a constant of nature with a recommended value traceable to the SI unit of length. The path of traceability of the Si lattice spacing is through x-ray diffraction measurements where the wavelength of the x-rays is referenced to that of one of the radiations recommended for the practical realization of the meter. Research at NIST is underway on developing techniques and artifacts for dimensional standards of step-height and linewidth based upon counting of Si lattice spacings [3]. While the lattice constant provides the connection to the SI unit, issues such as impurities, surface reconstruction, lattice defects and other effects must be accounted for in the uncertainty statement.

3.4 Traceability and measurement inference

Most measurement systems are capable of a nearly continuous output (down to the display resolution) but only a small sample of calibrated lengths is tested during an instrument calibration.[*] For example, survey tapes are typically calibrated at intervals of ten meters. The sampling of tape errors determined during the tape calibration is used to infer the accuracy of other lengths, provided an appropriate uncertainty statement can be produced. The results of the tape measurements are considered traceable even though it is highly unlikely that any particular measurement involves a length that has been directly compared to the SI unit. The situation is even more removed for complex measurement systems such as CMMs, laser trackers, and similar instruments. In these cases, the measurement traceability chain is linked to a finite number of calibrated lengths, typically traceable to an NMI, that are compared during the instrument calibration. Subsequent measurements often

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[†] Such uncertainty statements might involve the use of computer (Monte Carlo) simulation.

[*] The number and location of the calibrated lengths used in the comparison is usually left to standards bodies or other organizations that are experts in that particular field of technology. Typically, this involves engineering judgement to provide an assessment of all common error sources while being economically and technically practical.

involve completely different measurands, measured at locations that involve positions on the instrument's scales/encoders that have not been directly compared to the calibrated standards. These measurements are nevertheless traceable if an uncertainty statement can be constructed that connects the measurement under consideration to the calibrated length standards that provide traceability back to the meter. This procedure strongly invokes the "unbroken chain of information" interpretation of the unbroken chain of comparisons back to the SI unit of length.

The distinction between the connection to the SI unit and the associated uncertainty statement rapidly disappears under scrutiny. Indeed, the uncertainty statement implicitly connects to the SI unit since it evaluates the distribution of values, in terms of the SI unit of length, that could be reasonably assigned to the measured quantity. Similarly, the connection to the SI unit has in its chain of comparisons a long list of uncertainty statements describing the accuracy of the comparisons. Many of these uncertainty statements contain "Type B" uncertainty component evaluations that are merely educated guesses involving quantities that affect the comparison and are not physically connected to anything. This situation is illustrated in the following *gedanken* experiment. Suppose a meter length is needed on a shop floor and the environmental parameters have been carefully measured using calibrated instruments and the temperature is known to be 30 °C. In one case, a meter long NMI calibrated steel gauge block could be used, but the uncertainty statement will include a large component (about 10 μm) due to the uncertainty (at 30 °C) in the thermal expansion coefficient of the block. In this case, the connection to the SI unit is well established but the shop floor measurement accuracy will be dominated by environmental influences. In a second case, a HeNe laser could be used with nothing more known about it than the manufacturer certifies that it is operating on the 632.816 nm line. In this case the connection to the SI unit is through the physics of the Neon gain curve which is known to have a relative uncertainty (in the vacuum wavelength) of no more than $2 \cdot 10^{-6}$.[†] The index of refraction correction has very low uncertainty if the environmental parameters are well-known. Hence, the interferometric measurement of a one meter length on the shop floor, with a relatively large uncertainty associated with the connection back to the SI unit of length and small uncertainty associated with the environmental conditions will yield a better (smaller uncertainty) measurement than the NMI calibrated gauge block that has a small uncertainty associated with its connection to the SI unit but a very large uncertainty due to the thermal environment. We will discuss a similar industrial situation in the next section.

4. NIST PROGRAM IN "THE SHOP FLOOR AS NMI"

Research is also underway at NIST on developing techniques to support traceability of shop-floor dimensional measurements to the SI unit with minimal direct recourse to a dimensional calibration by an NMI. It is understood by NIST that attainment of such traceability directly to the SI unit would require, however, that a private institution would need to realize the SI unit of length in practice and satisfy the VIM definition of traceability, even as would an NMI for its own calibrations. Whether or not a private entity chooses to do so, from this paper's point of view, is an economic question, not a metrological one.

4.1 The origin of the notion of "Shop Floor as NMI"

A spectrum of U.S. manufacturers, from aircraft and automobiles through microelectronics and computer disc-drives, face simultaneously several technological trends which together require them to make measurements on the shop floor with characteristics that have historically been associated with measurements made at NMIs by professional metrologists.

First, shop-floor measurements in high-technology manufacturing have an ever increasing need for the highest metrological quality (i.e., accuracy) technologically attainable, a characteristic historically associated with only an NMI's measurements. In certain fields, such as fuel injectors, hydraulics, and semiconductor fabrication, the measurement accuracy needs exceed that of the NMI and companies have been forced to develop their own high accuracy capabilities. Consequently, in these specialized areas the NMI no longer serves as a low uncertainty connection to the SI unit.

Second, shop-floor measurements in manufacturing for the global market are being required by international product standards to satisfy new requirements associated with international standards to which they must conform to satisfy foreign customers. This includes the need to take uncertainty into account when determining whether a workpiece as made conforms to its specifications.

Third, the widespread rise of measurement accreditation programs is driving shop-floor measurements to have associated with them a stated measurement uncertainty, again a characteristic until now only associated with standards-laboratory measurements. Laboratory accreditation programs require explicit traceability to the international unit of length. These

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[†] For a typical HeNe laser the vacuum wavelength uncertainty is about $1 \cdot 10^{-6}$, however, if the wrong isotope of Neon is used this can increase the uncertainty to about $2 \cdot 10^{-6}$.

"laboratory" programs include many first article measurements, e.g., automobile components, that are not typically associated with a standards laboratory and have previously not explicitly been addressed with regard to the traceability issue.

4.2 Technical approach of SF-as-NMI Program

The "Shop Floor as NMI" program aims to provide a basis for both satisfying U.S. industry needs for traceability and reducing the number of NIST-provided task-specific length measurement services in both relative and absolute terms. The program goal is to (1) assist industry in connecting to the SI unit of length, (2) provide tools and information on the evaluation of measurement uncertainty, (3) assist in improving the accuracy of shop floor measurements, and (4) provide industrial education regarding issues such as traceability, calibration, decision rules, and uncertainty.

The program aims to develop methods by which industry may meet its own traceability needs without recourse to specialized NIST-provided calibrations or NIST-developed task-specific measurement capabilities or methods. The scope of the program includes no development of task-specific measurement services, capabilities, or methods themselves but rather is developing non-task specific tools and information that can be adapted to task-specific measurements on the shop floor. The non-task-specific methods and procedures are being co-developed by NIST and industry and include testing on the shop floors of industrial partners.

The technical approach also includes the development of proposals to key standards committees for formal adoption as standard practices. Relevant standards committees are the following subcommittees of the American Society of Mechanical Engineers Dimensional Metrology (B89) Committee: B89.1 - Length, B89.4 - Coordinate Measuring Technology, and B89.7 - Measurement Uncertainty. A set of procedures and methods would address how a shop-floor practitioner might realize, assert, and demonstrate traceability directly to the SI unit of length. In addition, throughout the proposed program, standards committees will also be used as focus groups for collaboration with industry on development of the standardized procedures and methods for making measurements and handling uncertainty under this new paradigm of "shop floor as an NMI".

4.3 Projects of the SF-as-NMI Program

The shop floor as an NMI program includes several projects, each typically of one year duration. For fiscal year 2001 the current projects include:

- development of a dilatometer and measurements of selected coefficients of thermal expansion of interest to industry
- a web site database listing most common engineering material coefficients of thermal expansion and their uncertainties together with a online tutorial
- development of a prototype multi-wavelength refractometer for measurement of long-beam-path index of refraction and identification of errors in the Edlen equation that limit its accuracy under shop floor conditions
- a web site that calculates the index of refraction of air and the estimated uncertainties together with an online tutorial
- development of a methodology for the rapid evaluation of dimensional distortions of workpieces due to non-uniform thermal environment
- development of documentary standards dealing with traceable shop-floor interferometry and CMM measurements of workpieces
- development of a laser based instrument for high accuracy calibration of ball bars in industrial environments
- development of software tools for the evaluation of CMM measurement uncertainty
- a web site and publications providing information on traceability, calibration and measurement uncertainty.

4.4 Case study involving an industry collaboration

Aircraft manufacturing is both a high technology and a government regulated industry. Measurement instrumentation is often state-of-the-art and relies on considerable metrological expertise to assure workpiece conformance to specifications. Due to the size of aircraft, the majority of measurements must be performed in large facilities with uncontrolled temperatures. Consequently issues such as the traceability of shop floor measurements is of considerable interest to The Boeing Company. NIST and Boeing have been collaborating in several areas of measurement technology and we describe here some activities regarding laser tracker systems on the shop floor. The goals in performing tracker compensation and calibration in a shop environment are (1) improved equipment utilization (reduced capital costs), (2) reduced corporate infrastructure (reduced operating costs), (3) improved utilization of personnel, and (4) improved accuracy.

Laser trackers are frameless coordinate metrology systems capable of measurements in a spherical volume of roughly 30 meters in radius. Until recently, these systems were compensated and calibrated in a temperature controlled (20 °C ± 0.3 °C) metrology facility. Tracker compensation involves a series of measurements to establish various software error compensation parameters. Tracker calibration involves determining the residual errors in the tracker after the compensation has been implemented. The calibration procedure derives its traceability from the use of a 2.5 meter length standard that is independently calibrated in the temperature controlled metrology environment. The particular calibration procedure to assess the laser tracker residual errors is currently being developed into a U.S. ANSI (American National Standards Institute) standard and has been a significant part of our collaborative effort [4]. A calibration apparatus designed to implement this calibration procedure has been constructed at NIST (see Fig 1) based on an earlier calibration system for evaluating large CMMs [5]. An identical apparatus has been delivered to the U.S. Navy for tracker calibrations in the defense department.

Figure 1. Laser tracker calibration apparatus.

One aspect of the shop floor as an NMI program is to consider the calibration concept from a broader perspective and in particular to consider *expanded* validity conditions [6] of measurement uncertainty statements that are applicable over the range of conditions, e.g., 10 °C to 30 °C (depending on the season), encountered during shop floor measurements. Initial concerns over shop floor calibration centered about the accuracy of the length standard used in a shop environment. Given a calibrated length standard how is its uncertainty affected by moving to a shop environment? Is it possible to perform an *in situ* calibration of the length standard using the interferometer on the tracker as the length standard? For a calibrated length moved to a shop environment, there are several sources of uncertainty including, (1) the reported uncertainty from the calibration lab, (2) the uncertainty in the thermal expansion coefficient used in applying a correction for thermal expansion, (3) the uncertainty in the temperature measurement of the length standard, and (4) thermal gradients in the length standard as a result of the non-homogenous environment of the shop floor. Of these four effects, the uncertainty in the coefficient of thermal expansion of the length standard is the dominant uncertainty contributor in typical shop environments. Since laser interferometers, like that on the laser tracker, can be accurately compensated for the thermal environment, the *in situ* calibration of the length standard using the tracker interferometer results in a significantly smaller uncertainty in the shop environment when the shop is significantly different from the calibration lab environment; see Fig 2. Index of refraction values for air can be evaluated using the NIST online “wavelength calculator” (http://patapsco.nist.gov/mel/div821).

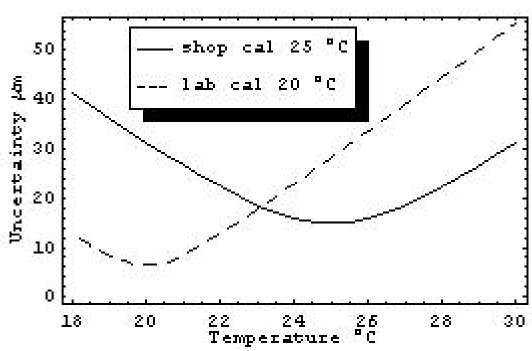

Figure 2. The uncertainty of a 2.5 m length calibrated on the shop floor at 25 °C and in the calibration facility at 20 °C.

One difficulty in constructing an uncertainty statement with expanded validity conditions based on calibration data taken in metrology (20 °C) conditions is the introduction of difficult to evaluate thermal-mechanical errors into the tracker structure. Laser trackers consist of a complex alignment of mechanical and optical components and predicting the behavior of this system at different temperatures is problematic. Testing of trackers at shop floor temperatures indicated the presence of these thermal-mechanical problems, as the observed errors were somewhat larger than those determined by the calibration in the

20 °C environment [7]. Shop floor compensation of laser trackers can remove much of the thermal-mechanical errors and is an effective means of improving measurement accuracy, since thermal conditions vary only modestly during the measurement period (the extended validity conditions allow no more than 2.5 °C variation during any one measurement period). Experiments to evaluate the effectiveness of this procedure have shown that the average error of shop floor compensated trackers is only 60 % of that of a metrology facility (20 °C) calibrated tracker‡, when a transverse length is measured in the shop floor environment; see Figure 3. Figure 4 shows this significant improvement as a function of measured length. (Radially oriented lengths show comparable errors between the two compensation methods as this measurement involves only the tracker's interferometer and does not involve its mechanical components).

Figure 3. Three trackers set up for radial length testing at the Boeing Company

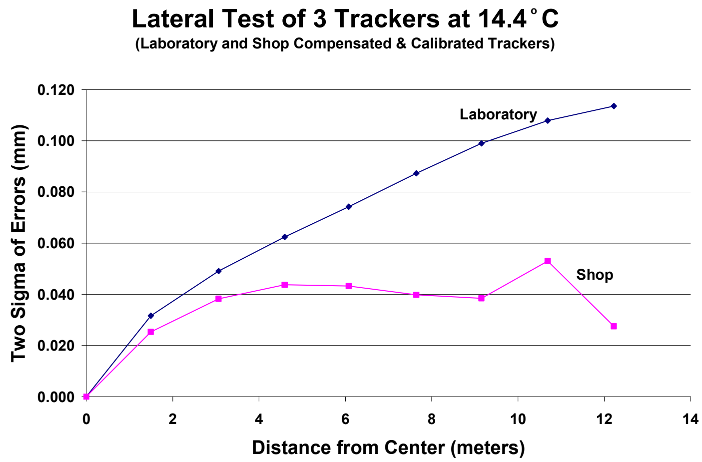

Figure 4. The measured residual errors of three laser trackers, each tested several times, as a function of the length measured, when calibrated both on the shop floor and in the laboratory.

Thus, Boeing has achieved modest improvements in tracker accuracy through reduced thermal-mechanical tracker errors. Our conclusion is that the resulting instruments are at least as good as the traditional metrology calibrated methodology when the shop environment differs significantly from standard (20 °C) metrological conditions. Hence, determination of whether or not to perform shop floor calibration is largely a business decision since the metrology issues have been addressed.

5. ISSUES OF TRACEABILITY TO THE SI

The traceability of industrial measurements to the SI unit of length raises several issues that do not normally occur in the traditional calibration laboratory field. This situation suggests the possibility, if not the desirability, of engagement by the international standards community with the related issues of:

(1) The equivalence of the "unbroken chain of information" with the "unbroken chain of comparisons" when establishing the connection to the SI unit.

(2) The clarification of when traceable measurements are needed on industrial products; the vast majority of products are not measured at all, and of the small percentage that are measured, those measurement results are not generally traceable as defined in the VIM.

(3) A clarification of what constitutes the minimal requirements for traceability of industrial measurements taking into account laboratory accreditation issue.

(4) The development of documentary standards, including recommended practices, on alternative paths of traceability to the SI unit, direct and indirect, for industrial dimensional measurements.

‡ Both the laboratory and shop floor calibrated trackers have evaluated length measuring errors that are within the expanded uncertainty assigned to the tracker instrument. Shop floor calibrations may allow a smaller expanded uncertainty to be assigned to these instruments and hence broaden their potential measurement applications.

6. SUMMARY

Two related developments at NIST in dimensional metrology include development by NIST of a formal NIST policy on traceability and a program to support the achievement by manufacturers of traceability to the SI unit of length in dimensional measurements without direct recourse to an NMI for dimensional calibrations. The latter program raises issues regarding the traceability of industrial dimensional measurements to the SI. While the newly-developed NIST policy on traceability asserts that it is not NIST's role to define, specify, assure, or certify traceability of measurements other than its own, NIST will actively collaborate with those whose role it is to do so, including international standards organizations. As a result, NIST is interested in and is willing to participate in addressing the issues identified.

DISCLAIMER

Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, or The Boeing Company, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

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